Experimental Investigation of the Physical Processes Applicable to a Magnetohydrodynamic Laser

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With a CO_2 probe laser the optimum small signal gain of magnetohydrodynamic (MHD) laser plasmas (typically 50 Torr, 1% CO_2, 0.001% Cs in He) has been found from an extensive parametric study to be 0.32% cm^{-1}. In the afterglow of the pulsed discharge, the relaxation rate of CO_2 (10^00) by CO_2-CO_2 collisions was 3.3×10^7 $atm^{-1}s^{-1}$, suggesting weak coupling between CO_2 (01^10) and CO_2 (10^00). The Cs-CO_2 reaction was so slow that in a typical cavity only 0.5% Cs would be lost. Quenching of Cs excitation by CO_2 is also negligible for MHD laser time scales. It is concluded that an MHD laser can provide higher specific power than either gasdynamic or electric discharge lasers, at thermal to optical conversion efficiencies of 2-3%.

Nomenclature

B	= magnetic field strength
$\bar{C}$	= mean thermal velocity
f_{Cs}	= cesium mole fraction
f_{CO_2}	= CO_2 mole fraction
I_0	= laser intensity
I_s	= saturation intensity
L	= laser cavity length
Li	= internal loss factor
M	= Mach number
N	= molecular density
n_{Cs}	= Cs number density
n_{CO_2}	= CO_2 number density
n_e	= electron number density
p	= static pressure
J	= current
K	= relaxation rate constant
T	= mirror transmissivity
T_0	= stagnation temperature
t	= time
Te	= electron temperature
Tg	= gas temperature
U	= flow velocity
$\nu_{Cs\text{-}CO_2}$	= collision frequency
α_0	= small signal gain
$\langle\beta\rangle, \beta_{app}, \beta_{eff}$	= average, apparent, and effective Hall parameters, respectively
$\langle\sigma\rangle, \sigma_{eff}$	= average and effective conductivity
δ	= loss parameter
τ_e	= relaxation time constant

I. Introduction

EXPERIMENTAL investigations have demonstrated that in nonequilibrium magnetohydrodynamic (MHD) generators the electron temperature can be elevated well above the gas temperature, creating a two-temperature plasma.[1,2,9] The existence of energetic electrons ($\sim 0.3-0.4$ eV) in a relatively cold, heavy species suggests the possibility of producing a population inversion in an appropriate gas additive. A MHD laser based on this effect should be capable of converting thermal energy into optical energy in one cavity at very high lasing power densities. The device has many attractive features. As the electrical power generated by the MHD process is delivered locally to the active medium, entirely within the flow, the uncertainties stemming from power conditioning and electrode phenomena inherent to electric discharge lasers may be avoided. Further, the high-speed flow which is essential for the removal of waste heat in high-power lasers is an intrinsic feature of the MHD laser. The process for inversion production being essentially local, there is a chance of achieving more uniform gain, hence better beam quality than in certain externally excited devices. The inversion may be extended to a much larger length along the flow than in a gasdynamic laser[13] providing more active volume for power extraction, and, hence, higher output power per unit of mass flow (greater than 12 kJ/kg). For the range of electron temperatures achievable in an MHD laser (3000-4000 K), molecular degrees of freedom are most suitable for excitation. The high quantum efficiency of its 10.6 μm transition and the well-understood kinetics of the CO_2 molecule suggest it as a most promising active species for MHD lasers.

In recent years several experimental and analytical investigations[3-8] of MHD lasers with CO_2 as an active medium have been reported. In 1969, while studying the effects of molecular additives (CO, N_2) on the performance of nonequilibrium generators, Kerrebrock and Draper[1,2] experimentally demonstrated that these molecules in concentrations on the order of several percent did not prevent the production of an elevated electron temperature and, in fact, that the vibrational levels of the molecule could be successfully coupled with the energetic electrons, thereby increasing their population. The first MHD laser experimental studies were performed at the United Aircraft Research Laboratories.[5] In a supersonic channel the inversion process in a mixture composed of 1% CO_2, 0.001% Cs, and $\sim$99.0% He was investigated and small signal gains up to $\sim 0.15\%$ cm^{-1} were measured. Zauderer et al.[6] at the General Electric Co. measured similar gains ($\sim 0.2\%$ cm^{-1}) in a mixture of 78% He, Ar, and 4% CO_2 with either 3-5% Xe or 0.1%Cs. A light-scattering measurement showed that the Cs concentration dropped by a factor of 5-7, possibly due to CO_2-Cs chemical reaction during the experiments, and it was concluded that for the laser to work the CO_2 mole fraction, f_{CO_2}, must be kept much higher than the

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Cs mole fraction, f_{Cs}. However, the ratio f_{CO_2}/f_{Cs} used was only ~ 40, compared to $\sim 3\times 10^3$ reported by other investigators.[4,7] In 1977 Biberman et al.[7] at the Institute of High Temperature of the USSR Academy of Sciences reported a self-sustained discharge experiment under 4.0 T magnetic field in a short-circuited, segmented MHD channel. In a laser mixture of 1% CO_2 + 0.001% Cs in He at a pressure of 15 Torr small signal gains up to $\sim 0.3\%$ cm^{-1} were estimated to have been achieved. The vast discrepancies in recommended gas compositions, measured and estimated small signal gains, and, consequently, projected laser power capabilities were attributed to several phenomena; quenching of the excited Cs atoms causing severe depopulation of the electrons,CO_2-Cs chemical reaction, evolution of ionization stabilities, and poor knowledge of the relaxation rates and mechanism of the lower laser level CO_2 (10^00).

In this paper the results of an experimental search for optimum gas compositions and electrical parameters for efficient operation of an MHD laser device will be summarized; and the consequences of the low-relaxation rate for the CO_2 (10^00)-CO_2 process measured during this investigation will be discussed.

The major contributions of this investigation toward understanding the physical processes applicable to an MHD laser follow.

A. Measurement of Small Signal Gain

The static simulation of the MHD laser has enabled the authors to study the kinetics of population inversion without the complications of a flowing system. The CO_2 and Cs injection techniques developed during the course of this investigation have enabled the formation of precise gas compositions during the tests.

B. Optimization of MHD Laser Plasma Parameters

Within the framework of small-signal gain measurements and of the static discharge simulation, optimum values for the MHD laser plasma parameters have been obtained. In an MHD laser cavity coupled for output power, the optimum value of CO_2 mole fraction will be much larger than the value presented here. The CO_2 mole fraction required to achieve a certain output power level can, however, be calculated with the knowledge of the relaxation kinetics of the CO_2 molecule developed here.

C. Measurement of Relaxation Rates for Lower Laser Level CO_2 (10^00)

By monitoring the afterglow of the discharge the relaxation rate of the CO_2 (10^00) level by CO_2 collisions has been measured. The measured rate is in close agreement with the analytical calculations of Seeber.[29] Since at CO_2 concentrations typical of MHD lasers (1-4%), the bottleneck is the CO_2 (10^00)-CO_2 collisions, this rate is an important input for calculations of the power output of an MHD laser.[8]

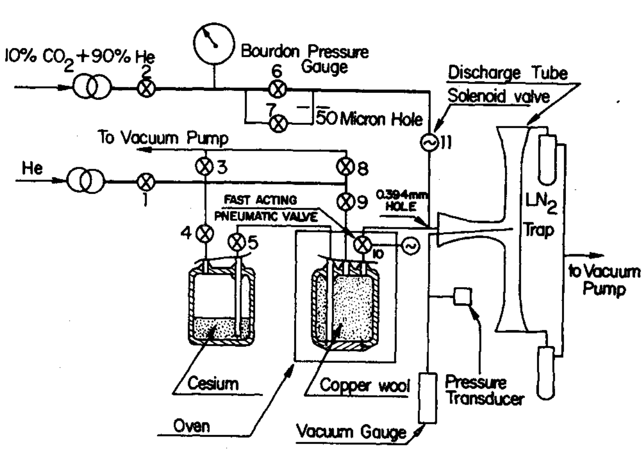

Fig. 1 Schematic of gas flow system.

D. Specific Power Estimates for MHD Lasers

Based on the measured small signal gain, the measured relaxation rate of the lower laser level CO_2 (10^00) and the "usable length" calculated by Walter[8] an estimate for the specific power achievable by MHD lasers has been made.

E. Measurement of Quenching Cross Section of Cs by Interactions with CO_2

The population of active Cs atoms is known to be depleted by Cs-CO_2 interactions in MHD plasmas. By monitoring the transient behavior of the Cs absorption diagnostics, the rate of Cs-CO_2 interaction has been measured, with the result that the Cs-CO_2 interaction under conditions typical of MHD lasers is so slow it will not effect the Cs population to any appreciable degree.

II. Experiments

A. Experimental Apparatus

The experimental facility utilized in the investigation simulates the flow-induced electric field of an MHD laser by an applied field and thereby eliminates the complexities and expense of a high-speed flow system. The experiments were conducted in pulsed mode, the features of which will be pointed out in the paragraphs to follow as various functions of the apparatus shown schematically in Fig. 1 are described individually. Helium is stored in a heated flask containing copper wool wet with liquid cesium. By opening a fast-acting pneumatic valve the Cs + He mixture is allowed to flow through the test chamber into vacuum; simultaneously another valve is opened to allow CO_2 to flow through the tube. At a predetermined time the magnetic field is turned on and the shutter to the CO_2 probe laser is opened. A few milliseconds later, the electric field is pulsed to pass a prescribed current through the gas mixture.

The discharge tube (the test section) is made from quartz with a 2.54-cm square cross section. This dimension was chosen so as to ensure that wall effects are small at the pressure level under investigation (50.0-70.0 Torr). At each end of the tube is an epoxy-fiberglass electrode block. Each block holds ten electrodes, each connected to a separate ballast resistor ($\sim 100\Omega$) to encourage a uniform discharge. The tube is terminated at each end by brass bellows and adjustable flanges that serve as window and mirror mounts required for multipass small signal gain measurements. Eight tungsten electrodes are fused to the side walls of the tube, which, being in contact with the plasma, allow monitoring of the axial as well as transverse (Hall) voltage.

The discharge circuit is powered by a 66 μF capacitor-bank chargeable to 4000 V. Two ignitrons are used as high-power switches, one to initiate and one to terminate the discharge. The duration of the discharge, i.e., the time difference between the triggering of the two ignitrons, is usually 200-300 μs, a time duration short enough not to thermally heat the plasma due to the input of electrical energy.

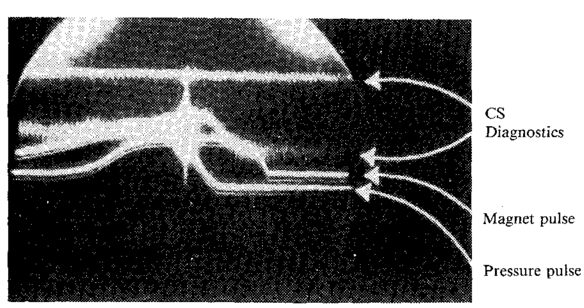

Fig. 2 Typical oscilloscope traces showing time histories of pressure, magnetic field, and transmitted Cs lamp intensity.

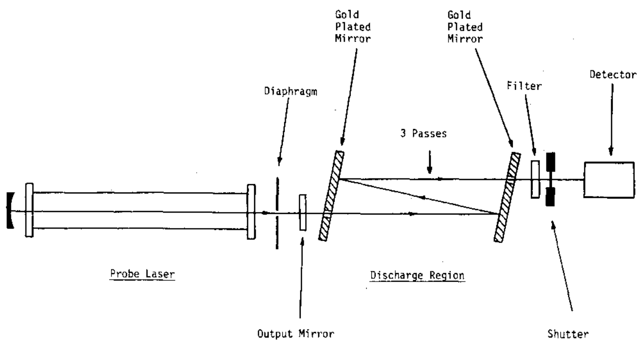

Fig. 3 Schematic of gain measurement, showing CO_2 probe laser, multiple passes in cavity and shuttered detector.

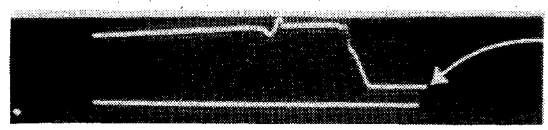

Fig. 4 Laser detector trace. Gain is indicated by the small rise superimposed on the large ramp, which is due to shuttering and amplifier rolloff.

The stainless steel vessel containing copper wool is flushed by liquid Cs before conducting a series of tests, so as to thoroughly wet the Cu wool. To keep the system at a uniform temperature the "pot" is enclosed in an oven (Fig. 1). Also, the pipe line from the pot to the discharge tube is heated by electrical tapes.

A electromagnet consisting of two rectangular Helmholtz coils surrounds the discharge tube. The magnetic field is nearly uniform ($\pm 0.3\%$) over most of the discharge region. The magnet, powered by a 500 μF, 3000 V bank of capacitors, is capable of providing a field up to 0.8 T in a square pulse for a duration of 2-3 ms.

B. Plasma and Laser Diagnostics

The diagnostic system consists of 1) electron temperature and number density measurement, 2) Cs concentration measurement, 3) estimation of CO concentration in the plasma, 4) electrical current density measurements, and 5) axial and transverse (Hall) voltage measurements.

By monitoring the Cs continuum radiation at two wavelengths[34-36] (4904 and 4285 Å) the electron temperature and electron number density are determined. The concentration of metallic Cs in the discharge has been especially troublesome to measure in MHD laser investigations. In the present study it was determined by measuring the resonance absorption at 4550 Å of light from a Cs spectral lamp. To minimize noise and record a reference on each scope trace the light from the Cs lamp was chopped at about 20 kHz. Figure 2 shows typical time variations of the pressure in the chamber, of the magnetic field, and of transmitted intensity from the Cs lamp. Time advances from right to left. The top trace labeled "Cs Diagnostics" is the value with the Cs light shuttered, the lower is the transmitted signal, so the reduction of the difference of these is the measure of Cs concentration. This measurement was highly reproducible. The system was calibrated with two quartz test chambers sealed off with 60 and 120 Torr of He. In earlier experiments[4] with MHD laser plasmas it was suspected that CO_2 had dissociated to CO and O_2 during the discharge, so radiation at the 5052 Å triplet band of CO was monitored. As mentioned before, the Hall and axial fields were measured by probes in contact with the plasma.

The probe laser is a cw electric discharge CO_2 laser with semispherical cavity consisting of a gold-plated mirror ($R \sim 10$ m) and a germanium semitransparent ($T = 10\%$) mirror placed about 1.5 m apart. The 10.6-μm laser beam is allowed to make three passes through the test chamber to fall on an electronically operated shutter placed before the liquid N_2 cooled HgCdTe infrared detector (Fig. 3). The shutter is opened just before the discharge to provide a reference during each experiment. A typical trace is shown in Fig. 4, where time increases from right to left. The large increase corresponds to shutter opening, the slow decrease to the rolloff of the A.C. coupled amplifier. The gain measurement is contained in the short transient near the center of the trace. It is shown expanded in Fig. 5. In order to measure the unsaturated gain, the intensity of the probe laser was kept below 6.0 W/cm^2.

The experiments were planned to illuminate the basic kinetics of inversion in CO_2 under MHD conditions, the main task of this investigation. The experiments were divided into two categories, without and with magnetic field, thereby isolating the effects of turbulence in the MHD plasma from other phenomena.

C. Measurements without Magnetic Field

The laser-gain data without magnetic field provides information on collisional excitation and relaxation of CO_2 molecules in a Cs seeded He plasma. Keeping the pressure in the test chamber between 33.0 and 70.00 Torr, for various values of J_x, f_{Cs}, and F_{CO_2}, laser gain was measured as a function of time. A typical gain trace is shown in Fig. 5.

The transient behavior of the gain is a very important feature of this investigation. The complex kinetic processes which occur in the plasma as it flows downstream in an actual laser are displayed as a temporal analog during the pulse. The time scale for relaxation processes to attain equilibrium ranges from 1 to 10 μs; for most of the experiments it has been on the order of 5.0 μs. Thus, gain (or absorption) lasting more than 5 μs is a result of fully developed inversion kinetics and has been regarded as valid experimental data. In some cases during the 300 μs discharge pulse it has been possible to obtain several valid experimental gain measurements.

The current density J_x was varied from 0.2 to 0.75 A/cm^2, and CO_2 mole fraction from 0.74 to 4.7%, the Cs mole fraction from 8.0×10^{-6} to 3.0×10^{-4}. A small signal gain up to 0.3% cm^{-1} was measured. To study the effect of each individual parameter on the inversion process over 150 data points were taken in sets such that for each set the parameter in question was kept constant at a particular value while all other parameters were scanned through the relevant ranges. The peak gain value for this particular value was recorded. The process was repeated for all available values of the parameter and, thus, a master plot was obtained. Such plots showing the dependence of gain on f_{Cs} and f_{CO_2} are shown in Figs. 6 and 7, respectively.

As the Cs mole fraction is increased from $\sim 8.0\times10^{-6}$ to 1.4×10^{-5}, a rapid rise in gain is seen, indicating a strong positive dependence of CO_2 (001) level excitation on electron number density. Further increase in the seed fraction causes gain to decrease, but rather slowly. The electron number density near the peak is recorded to be $\sim 2\times10^{19}$ m^{-3}. At electron number densities higher than this electronic excitation of the CO_2 (10^00) becomes important and, hence, the decline in population inversion. The graph also suggests that an MHD laser operating with seed mole fractions below 1.4×10^{-5} will not be a practical device, as gain is too sensitive to fluctuations in f_{Cs} in that zone. The seed mole fraction should thus be kept in the vicinity of 1.4×10^{-5}-2×10^{-5}.

Calculations show that for CO_2 concentrations of interest the gain profile in MHD lasers is pressure broadened, dominated by CO_2-He collisions. Thus the small signal gain is proportional to the population inversion normalized to the total number of neutral species. The dependence of gain on f_{CO_2} can be seen in the master plot shown in Fig. 7. Initially, as expected, gain rises linearly, with increase in molecular population. However, after reaching a maximum of 0.32%

cm^{-1} at 0.93% CO_2 concentration the gain starts to drop at a much slower rate than the rise. The adverse effect on the inversion may be attributed to the following reasons: overcrowding of the laser lower level; increased inelastic losses of electron energy to CO_2 molecules, as the relative number of the latter grows; and quenching of the excited Cs atoms. Lowenstein[3] studied the effect of quenching of Cs atoms on the inversion process, assuming the Cs-CO_2 quenching cross section to be equal to 70 Å^2 (since data on Cs-CO_2 quenching were not available) and concluded only 0.2% CO_2 could be allowed in the laser cavity without causing a severe reduction in electron number density. However, in this study and other published reports[5-7] the measured gain has been much larger than the value reported by Lowenstein (~0.02% cm^{-1}) at larger CO_2 concentrations (Table 1). It is concluded that the cross section assumed by Lowenstein for CO_2-Cs quenching was much too high. Walter[8] concluded as a result of his analytical study that if the plasma is preionized before entering the laser cavity, i.e., before the start of MHD interaction, the effect of quenching would be negligible.

Walter[8] did not take the effects of Cs-CO_2 chemical reaction into account, since no data on the reaction rate were available. During this investigation the rate was measured and found to be much too slow to have any significant effect on the Cs population. The severity of the quenching process is approximately proportional to the ratio f_{CO_2}/f_{Cs}; the dependence of gain on this ratio can be seen in Fig. 8. Shaw[34] reports that the depression of electron number density from the Saha value is gradual, as the quenching rate increases, and at a critical value the electron number density is severely reduced. When the ratio f_{CO_2}/f_{Cs} reaches a value of 700 (Fig. 8), the gain starts to decline rather rapidly, indicating that loss due to the quenching process has become important.

During the experiments current density was chosen to control the electrical properties of the plasma. In the flowing system both U and B, along with f_{CO_2}, f_{Cs}, and p, have to be defined to create any desired plasma condition (for a fixed value of magnetic field), however, in this investigation the current density serves as the closing link. The number density of electrons, their distribution function and average temperature are uniquely defined, consequently, so are the excitation and deactivation rates of laser levels by the current density. For fixed values of f_{CO_2}, f_{Cs}, and p there exists an optimum current density at which the gain is maximum. For a clearer view the small signal gain for two gas compositions has been plotted against the corresponding conductivities in Fig. 9. The curve for the gas composition with $f_{Cs} = 10^{-5}$ and

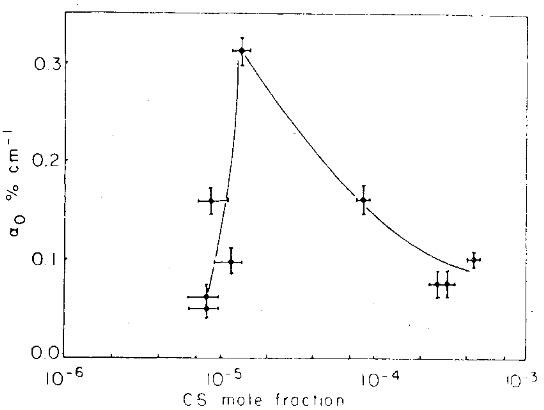

Fig. 6 Small signal gain as a function of Cs mole fraction. Each point optimized in other variables.

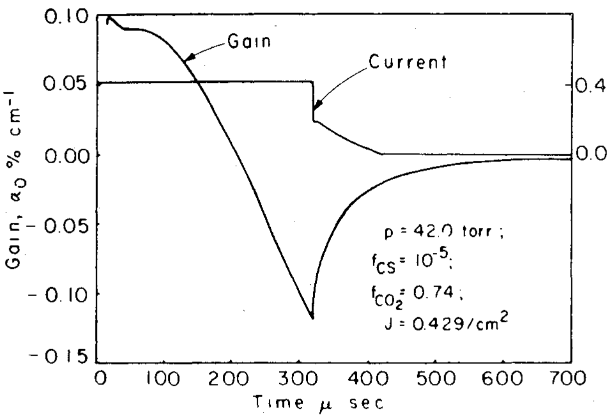

Fig. 5 Typical current and gain time variations.

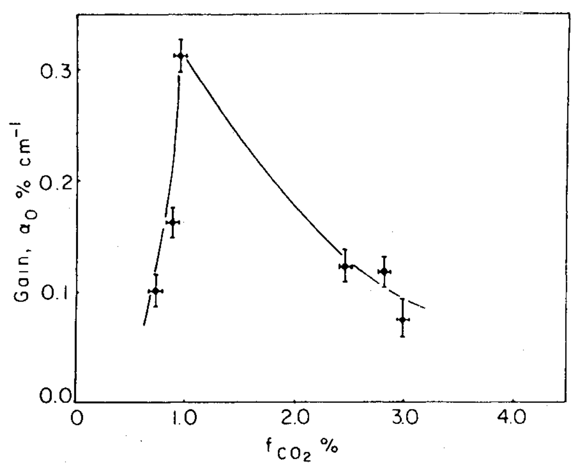

Fig. 7 Small signal gain as a function of CO_2 mole fraction. Each point optimized in other variables.

Table 1 Summary of report values of CO_2 (10^00)-CO_2 (01^10) relaxtion rates

Investigators	Methodology	Rate (atm^{-1} s^{-1})
Rhodes et al.[25]	Absorption at 10.6 μ (1968)	3.0×10^8
Seeber[29]	Calculations (SSH theory) (1971)	3.4×10^7
Bulthuis and Ponsen[30]	Power decay in the afterglow (1972)	9.9×10^6
Rosser et al.[24]	Electric pulse, measured 4.3 μ decay and gain at 10.6 μ (1972)	7.6×10^5
Bulthuis	Power decay (1973)	7.7×10^6
Present work	Measured gain at 10.6 μ (1978)	3.3×10^7

$f_{CO_2} = 0.74\%$ at $p = 42.0$ Torr is symmetrical with a maximum of $\sim 0.10\%$ cm^{-1} at 5.25 mho/m. As the conductivity is increased from 3.0 mho/m, the inversion gradually increases, as the electron number density increases, and reaches an optimum value. Due to the low CO_2 concentrations, the electron temperature can be elevated beyond the 3500-4000 K range, where the excitation of lower levels becomes significant and gain drops. At the other gas composition, where $f_{CO_2} = 2.47\%$ and $f_{Cs} = 6\times10^{-5}$, increase in the conductivity reduces the gain at a slower pace, for the reasons discussed earlier.

D. Experiment with Magnetic Field

The data taken without magnetic field provide a knowledge of the excitation and relaxation process of CO_2 molecules in a uniform plasma. In order to study the effects of nonuniformities due to electrothermal waves, experiments with magnetic field were conducted. The nonuniformities in an MHD plasma profoundly influence electron temperature elevation and average Joule dissipation of energy in the gas. In the limit when $\langle\beta\rangle > \beta_{crit}$[14-16] a "turbulent state" is reached with an anomalous increase in resistivity. As shown in Fig. 10, the small signal gain has been found to increase with increasing magnetic field. At $f_{CO_2} \simeq 0.74\%$, as the value of $\langle\beta\rangle$ increases, gain rises and saturates at 0.32% cm^{-1}, the maximum value measured in absence of the magnetic field. As the CO_2 concentration is increased, the value at which gain saturates drops, which is in agreement with the master plot of Fig. 7. The electron temperature rise due to Joule dissipation[15] takes the following form.

$$\frac{Te-Tg}{Tg} = \frac{\gamma}{3\delta'} M^2\langle\beta\rangle^2 \frac{\sigma_{\rm eff}}{\langle\sigma\rangle}\cdot\frac{1+\beta^2_{\rm app}}{1+\beta^2_{\rm eff}} \qquad (1)$$

It should be noted that n_e does not directly affect the expression and Joule dissipation can be measured in terms of $(Te-Tg)/Tg$, the maximum value for which has been found from the experiments to be close to ~ 9.0. For any CO_2 concentration, an appropriate selection of f_{Cs} and $(Te-Tg)/Tg$ would provide the desired plasma conditions for an effective inversion. For the conditions achieved in these experiments at $\beta = 0.5$ T ($\langle\beta\rangle, \beta_{\rm eff}, \sigma_{\rm eff}/\langle\sigma\rangle$), in order to create the desired dissipation, i.e., $(Te-Tg)/Tg \simeq 9.0$, the Mach number required would be $\simeq 4.4$, which might not be practical from a fluid mechanical point of view. However, the desired dissipation can be achieved by increasing β and, therefore, $\langle\beta\rangle$ at lower Mach number.

E. Relaxation Rates for the Lower Laser Level CO_2 (10^00)

As is required for efficient laser operation, the relaxation rates for CO_2 (00^01), the upper laser level, are very slow, and are well known. However, although since 1966 at least ten experimental studies[17-23] have been performed, as yet neither the basic mechanism of the CO_2 (10^00)-CO_2 relaxation nor any universally acceptable data on its rate is available. In electric discharge and other CO_2 lasers, where the CO_2 concentration is on the order of 10-20%, the lower laser level [CO_2 (10^00)-CO_2 (02^00)] is very rapidly deactivated by CO_2-CO_2 collisions in comparison to the CO_2 (01^10)-He collisions. However, at CO_2 concentrations typical of MHD lasers 1-4% the bottleneck rate is determined by the CO_2 (10^00)-CO_2 collisions. Most confusion arises from the existence of the Fermi resonance between the 10^00 level and the doubly degenerate 02^00 level of the bending mode. The most common belief is that 10^00 and 02^00 are strongly coupled with each other, and the relaxation process can be summarized as [CO_2 (10^00), CO_2 (02^00)] $\rightarrow CO_2$ (01^10). Rates for the CO_2 (10^00)$\rightarrow CO_2$ (01^10) process have been measured by several investigators and are listed in Table 1. The spread between the reported rates is as large as 3 orders of magnitude.

By monitoring the afterglow of the discharge the relaxation rate of the 10^00 level by CO_2 collisions has been measured. When the discharge is short circuited, electronic pumping of the levels ceases and the system in time approaches an equilibrium state. The transient behavior of the population can be described as:

$$N_t = N_{\rm equi}\exp(-t/\tau_e) \qquad (2)$$

Since the time constant for the relaxation of the upper laser level is large, the decay of laser power measures the relaxation

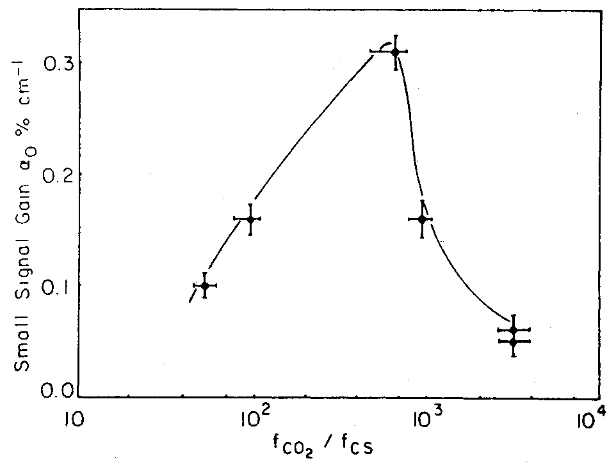

Fig. 8 Small signal gain as a function of ratio of CO_2 to Cs concentrations. Each point optimized in other variables.

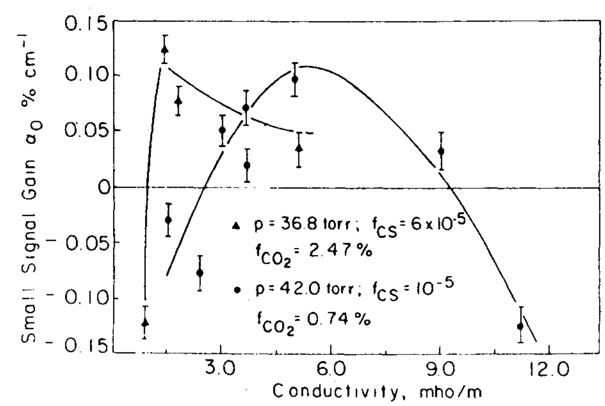

Fig. 9 Dependence of small signal gain on electrical conductivity for two gas pressures and compositions.

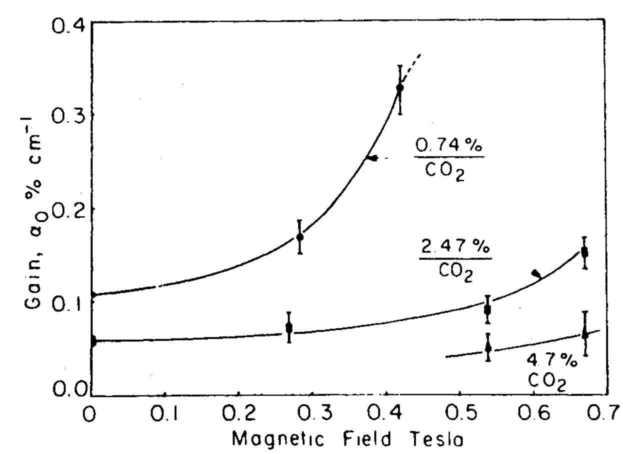

Fig. 10 Small signal gain as a function of magnetic field for three CO_2 mole fractions.

of the lower level by He and CO_2 collisions. The time constant can be expressed as

$$\frac{1}{\tau_e}=\frac{1}{\tau_{e,\mathrm{He}}}+\frac{1}{\tau_{e,\mathrm{CO_2}}} \tag{3}$$

Using the definition of the rate constant Eq. (3) can be modified to the form

$$\frac{1}{\tau_e p}=k_{\mathrm{CO_2}}-\mathrm{He}+f_{\mathrm{CO_2}}(k_{\mathrm{CO_2\text{-}CO_2}}-k_{\mathrm{CO_2\text{-}He}}) \tag{4}$$

Values of $1/\tau_e p$ have been plotted against their respective CO_2 concentrations in Fig. 11 and the following rate constants were determined.

$$k_{\mathrm{CO_2\text{-}He}}=(7.5\pm0.5)\times10^4\ \mathrm{atm^{-1}\ s^{-1}}$$

$$k_{\mathrm{CO_2\text{-}CO_2}}=(3\pm0.3)\times10^7\ \mathrm{atm^{-1}\ s^{-1}}$$

The CO_2-CO_2 rate very closely coincides with the rate calculated by Seeber[29] and is of the same order of magnitude as reported by Bulthuis and Ponsen.[30] The rates reported for the Fermi resonance, CO_2 (10^00)-CO_2 (02^00), (except by Stark) are slower than the rate measured for the CO_2 $(10^00)\rightarrow CO_2$ (01^10) process, indicating the bottleneck rate is determined by the Fermi resonance. However, if the explanation given by Stark is correct, then another process, in this case CO_2 $(10^00)\rightarrow CO_2$ (01^10) relaxation determines the bottleneck.

F. Rate of Cs-CO_2 Interaction

By monitoring the transient behavior with the Cs absorption diagnostic, the rate of the Cs + CO_2 chemical interaction has been estimated. For this purpose it has been assumed that the rate of interaction can be written in the form

$$\nu_{\mathrm{Cs\text{-}CO_2}}=n_{\mathrm{CO_2}}\cdot Q_{\mathrm{Cs\text{-}CO_2}}\cdot\bar{C}_{\mathrm{CO_2}},\ \mathrm{s^{-1}} \tag{5}$$

where $Q_{\mathrm{Cs\text{-}CO_2}}$ is the cross section for the process. Several experiments were conducted in sets of two: with and without CO_2, and the time history of total Cs atoms lost was plotted.

$$(\Delta n_{\mathrm{Cs}})_{\mathrm{tot}}=\int_0^t n_{\mathrm{Cs}}n_{\mathrm{CO_2}}Q_{\mathrm{Cs\text{-}CO_2}}\bar{C}_{\mathrm{CO_2}}\mathrm{d}t \tag{6}$$

By numerical differentiation of $(\Delta n_{\mathrm{Cs}})_{\mathrm{tot}}$ the cross section was computed to be in the range of 1.3×10^{-24}-4.6×10^{-24} $\mathrm{m^2}$. The exact nature of the Cs + CO_2 chemical reaction is not known, but two possible processes have been cited:

$$CO_2+Cs\rightleftharpoons[CO_2Cs]_x \tag{7}$$

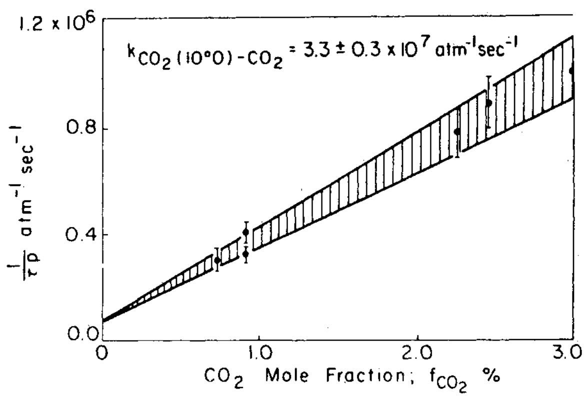

Fig. 11 Relaxation rate of lower laser level by CO_2 mole fraction.

and

$$CO_2+2Cs\rightleftharpoons CO+Cs_2O \tag{8}$$

It should be noted at this point that in order to minimize the interaction between Cs and CO_2, in the proposed configuration for MHD laser, as in this experiment, CO_2 is not premixed with the He and Cs. Rather, it would be injected into the cavity just before or after the nozzle. Thus, the effective interaction time for Cs and CO_2 would be the flow time through the cavity length.

Based on the cross section measured, at a typical pressure of 0.1 atm, the characteristic time for the chemical reaction with 3% CO_2 would be about 30 ms, whereas the residence time in a 0.5-m cavity (Mach number = 3.0) would be only 0.17 ms. Thus, in a typical MHD laser cavity only $0.17/30=5.6\times10^{-3}$ of the Cs number density would be lost.

III. Discussion

During the inversion process complete redistribution of CO_2 molecules amongst their vibrational levels takes place and the effective value of the inelastic loss factor $\delta_{\mathrm{CO_2}}$ goes down as much as 50%. From the relaxation data it is clear that the levels in the bending mode relax much slower than would be required to attain a Boltzmann distribution within the mode. The levels of 02^00, 01^10, 03^20 should be described by three different temperatures, and one would require a "five-temperature" model to describe the plasma. The "three-temperature" model of Walter[8] predicts gains in the range of 0.1-0.15% ($T_0=2090$ K), however, he points out that if the stagnation temperature is lowered to 1800 K gain may reach a value of 0.21%, and it seems perfectly plausible that if T_0 is reduced further the calculated small signal gain may rise to the measured value of 0.3% $\mathrm{cm^{-1}}$. Biberman et al.,[7] by extrapolating from the losses in the cavity, came to the conclusion that a small signal gain of 0.3% $\mathrm{cm^{-1}}$ was achieved in their experiments, which equals the value measured in this investigation. Also, the specific laser power extracted in their experiment (~ 10 KJ/Kg) is very close to the predicted value in this investigation.

The measured gains are quite large (by MHD standards) and although, due to the low concentration of CO_2 molecules, the deactivation of the lower laser level is slow, the MHD laser is capable of delivering high-power densities. In its simplest form, the expression for the intensity extractable from a laser cavity may be written as[37]:

$$I_0=\frac{P_0}{A}=2I_s\left[\frac{\alpha_0 L}{Li+T}-1\right]T \tag{9}$$

The magnitude of I_s, the saturation intensity, depends exclusively on the physical properties of the laser mixture, and on its composition and static pressure, and increases directly proportional to p^2. For estimates of I_s, Walter's[8] numerical study has been used. Walter treated each mode individually, assuming a vibrational temperature associated with each mode, and used relaxation rate constants very close to the values measured during this study. The calculations show that laser intensities as large as 1 $\mathrm{KW/cm^2}$ can be coupled out from an MHD laser cavity ($L\sim0.5$ m), however, the overall optical energy that can be extracted from the gas depends upon the length along the channel within which the inversion can be maintained. The "usable length" depends upon the design of the channel, gas composition, and $J\times B$ force. Walter,[8] using the dimensions of the M.I.T. experimental nonequilibrium generator and an analytical model of the plasma dynamics developed by Solbes, calculated the usable length for various CO_2 concentrations (Mach number = 4.0, $B=4.0$ T), which varies from 10 cm to 1% CO_2 to ~45 cm for 3% CO_2 concentration. Using the small-signal gain measured in this study and the results of Walter's investigation, specific power density extractable from an MHD laser is calculated and is compared in

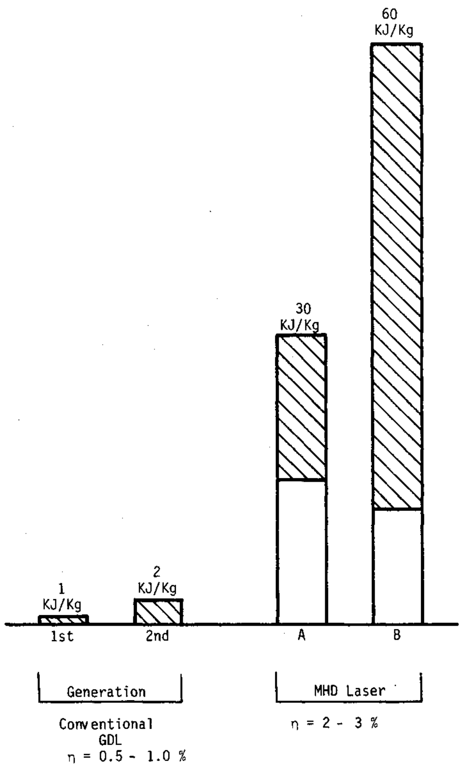

Fig. 12 Comparison of power densities and efficiencies of gas dynamic lasers to those of MHD lasers, η is thermal to optical conversion efficiencies. Bar B shows estimate of Ref. 8, while A represents results of this work. Shaded area represents range of estimates.

Fig. 12 with the specific power of gasdynamic laser systems. The estimates range from 15.0 to 30.0 kJ/kg.

IV. Conclusion

The small-signal gains measured range from 0.06% cm^{-1} to 0.32% cm^{-1} with optimum Cs mole fraction of $\sim 1.4\times 10^{-5}$. In order to provide appropriate Joule dissipation, the nondimensional parameter $(Te-Tg)/T_0$ should be kept around 9.0, which may be achieved by selecting proper M and $\langle\beta\rangle$ (i.e., B field). The electron temperature determined by this parameter in conjunction with the Cs mole fraction would provide the required electron number density. At low CO_2 concentrations higher gain is achievable, however, due to the highly "turbulent" plasma inversion does not last more than 5 μs. This phenomenon has been confirmed by the analytical study conducted by Walter,[8] where in a flowing system (Mach number = 4.0) lasing stops after 20 mm of travel $(2\times 10^{-2}/4300 = 4.6\ \mu s)$. At higher CO_2 concentrations, the plasma is stable and provides higher specific laser power. When compared with existing laser systems, the MHD laser device seems to be a promising competitor in the field of high-power lasers. With the new understanding of nonequilibrium plasmas and the better numerical models[9] and knowledge acquired by this experimental investigation and by the numerical study of Walter[8] a feasibility study of MHD lasers can be made.

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